ERAOF: A New RPL Protocol Objective Function for Internet of Things Applications

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***Abstract*—Since its definition, RPL (the IPv6 Routing Protocol for Low-Power and Lossy Networks) has been emerging as the standard protocol for routing in Internet of Things (IoT) solutions. RPL is a proactive routing protocol that performs the process of route creation based on Objective Functions (OFs). The OFs are responsible for defining rules and constraints to select the best paths considering different routing metrics. In its definition, RPL does not impose the use of a default OF and indicates that an OF should be selected according to the application. Thus, this paper proposes an Energy Efficient and Path Reliability Aware Objective Function (ERAOF) for IoT applications that requires energy efficiency and reliability in data transmission. The ERAOF is based on the composition of energy and link quality routing metrics. Results show that ERAOF is able to improve the network performance when compared to other OFs available in the literature.**

I. Introduction

Internet of Things (IoT) is regularly defined as a novel paradigm that enables the communication among things (assuming that any object can be connected to the Internet) in a ubiquitous and pervasive way through different technologies [1]. IoT application scenarios can cover various environments around people and be widely diverse, such as the following: urban sensor and actuators networks [2], industrial monitoring [3], and home automation [4]. In order to allow an IoT application fulfilling its objectives with efficiency, it is necessary that a routing protocol can provide data communication in an efficient way [5]. The routing protocols should take into account the different application requirements, such as low latency, high reliability, and efficient energy consumption.

Among the routing protocols used in IoT, RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [6] has been emerging as the *de facto* standard solution [7]. RPL is a routing solution based on IPv6 proposed by IETF (Internet Engineering Task Force) and projected for Low power and Lossy Networks (LLN). The popularity of RPL grows constantly justified by its high flexibility for different applications, QoS (Quality of Service) support, security resources, among others [8]. The high flexibility of RPL enables it to be used in several applications and fulfill different network requirements. The component responsible for providing the adaptation of the protocol to the exigencies of a given application is the Objective Function (OF). The OF allows the route selection based on the routing metrics according to the interest of each application.

Although several OFs have been proposed for RPL, few of them are designed to attend the requirements of IoT applications. Thus, this work proposes the Energy Efficient and Path Reliability Aware Objective Function (ERAOF), a new objective function for IoT applications that require high reliability and efficient energy consumption. To reach its goal, the ERAOF merges the metrics of Energy Consumed (EC) and Expected Transmission Count (ETX) at the moment of a route selection. Taking into account the EC, ERAOF can avoid the use of paths with low remaining energy levels. At the same time, the influence of ETX allows the ERAOF to select paths with a high probability of success in the packet transmission. Thus, it is expected that ERAOF can fulfill the requirements of an IoT application that demands high reliability with an efficient energy consumption.

The rest of this paper is organized as follows. Section 2 describes the RPL protocol and some important related works available in the literature are presented in Section 3. Section 4 describes the proposed ERAOF while the performance evaluation study and results are analyzed in Section 5. Finally, Section 6 concludes the paper and suggests future works.

II. IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL)

RPL is a routing protocol for LLNs, created by the RoLL working group and defined by IETF as the standard routing protocol for 6LoWPAN networks (IPv6 over Low power Wireless Personal Area Networks). RPL describes a method of constructing a logical topology called Destination Oriented Directed Acyclic Graph (DODAG) [9] where the DODAG root is the gateway (or sink) node (Figure 1). The DODAG is built based on Objective Functions (OFs) that define the best paths in the network considering several routing metrics as number of hops, latency, delivery ratio, node energy, throughput, link quality, and transmission reliability [10]. The OF allows the nodes selecting its preferred parent in a set of neighbor reachable with just one hop. At the moment of data message forwarding, the selected preferred parent is used as a path for reaching the DODAG root.

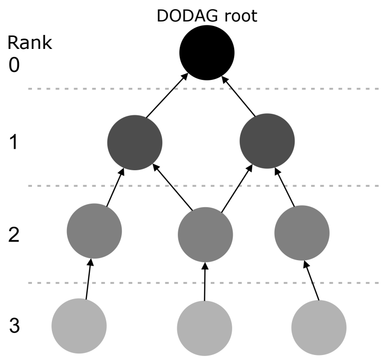

Fig. 1. Illustration of the DODAG graph.

The protocol supports three different traffic patterns: multipoint-to-point (MP2P), point-to-multipoint (P2MP) and point-to-point (P2P) [11]. In the first (MP2P), the nodes of the DODAG send the data to the root. In the second (P2MP), the DODAG root sends data/actions to the other nodes. In the last (P2P), the network nodes send messages to the other nodes (non-root) of the network.

In its definition, RPL specifies four types of control messages for network maintenance and information exchange. The first type is called DODAG Information Object (DIO) message and represents the primary source of routing control. The second is called Destination Advertisement Object (DAO) message, which is responsible for enabling the downward data traffic. The third type is DODAG Information Solicitation (DIS) message, which makes it possible for a given node to request a DIO message from any reachable neighbor node. The fourth type is the DAO-ACK message that is sent in response to a received DAO message [12].

The protocol tries to avoid loops through the computation of the position representative value of each node inside of DODAG, called Rank. The Rank value is computed based on the used OF and must comply some general properties as monotonicity.

The protocol is performed in four phases:

- **Configuration Phase**: the construction of the network topology begins at the configuration phase. On this phase, the root node broadcasts DIO messages. All the nodes that receive a DIO message, add the root in a routing table. This table stores the address of the neighbor nodes that can be used for possible upward or downward future communications.
- **Route Establishing Phase**: the nodes compute its Rank based on the information received in the DIO message. If the computed Rank is higher than the Rank inside of the DIO message, the node selects the DIO sender as its preferred parent. When a new device desires to join the network, it must send DIS messages requesting DIO of its neighbors. Thus, all the nodes in the neighborhood that receive a DIS must answer with a DIO for this new device in order to compute its Rank in the DODAG.
- **Data Communication Phase**: the data messages flow in the network with destination to the root according to the routes selected in the route establishing phase. Based on the traffic pattern, the data traffic can occur in an upward or downward fashion.
- **Path Repair Phase**: due to the inherent features of network topologies, the routes to the root change by several factors. Some reasons include changing of the preferred parent, external interferences in the communication links, and battery exhausting. The changes in the upward routes require updating of downward routes. Thus, a DAO message must be sent every time a route is updated or whether the preferred parent is changed.

III. Related Works

In the last years, several studies have been performed to the specification and deployment of objective functions in RPL using the recommended metrics for the LLNs (Low power and Lossy Networks). This section reviews the main relevant objective functions available in the related literature.

The default OF for RPL, which is called OF0 (Objective Function Zero), was designed to enable interoperability between different implementations of RPL [13]. OF0 presents a simple operation and does not use routing metrics in the rank definition. A node chooses as its preferred parent the reachable neighbor that has the lowest rank. Given a node n, its rank is defined by $R(n)$ as shown in Equation 1.

$$R(n) = R(P) + rank_{increase} \quad (1)$$

Where:

$R(n)$ is the new rank of the node (n);

$R(P)$ is the rank of the preferred parent;

$Rank_{increase}$ is a variation factor (delta) between the ranks of the parent and the node, expressed by the Equation 2.

$$rank_{increase} = (Rf \cdot Sp + Sr) \cdot MinHopRankIncrease \quad (2)$$

Where:

Rf is a configurable factor that is used to multiply the value of the link property. By default, it uses the value 1;

Sp is the step of the Rank;

Sr is the maximum value assigned to the Rank level to allow a viable successor;

$MinHopRankIncrease$ is a constant variable whose default value is 256.

In [14], the authors present the Minimal Rank with Hysteresis Objective Function (MRHOF). The MRHOF is based on the metric container concept that explains a set of metrics properties and/or constraints to be considered in the routing process. MRHOF is compatible only with additive metrics as specified in RFC 6551 [10]. Preferred parent selection is based on path cost considering the adopted metric where routes that minimize the cost associated with metric are preferred. By default, the MRHOF uses ETX [15] for measuring the quality of links among the nodes. ETX estimates the required average number of transmissions, including retransmissions, so that a packet is correctly delivered to the destination. The ETX is defined according to Equation 3.

$$ETX = \frac{1}{Df \cdot Dr} \tag{3}$$

Where:

Df is the probability of the packet being received by the neighbor;

Dr is the probability that the acknowledgment is successfully received.

In [16], the authors present a performance evaluation study analyzing the combination of four metrics: hop count, ETX, RSSI (Received Signal Strength Indicator), and remaining energy. The metrics are combined in pairs using lexical or additive composition. In the additive composition, the node rank is calculated based on a weighted sum of the used metrics. In the lexical composition, a node selects the neighbor with the lowest (or highest) value based on the first metric, just if these values are equals, the node compares the second metric. The results shown that the performance of the studied combinations is dependent of the order of metrics priority.

In [17] is proposed an objective function based on fuzzy logic, named OF-FL. This function combines a set of metrics including point-to-point delay, ETX, hop count, and battery energy level, providing routing decisions to the network nodes during preferred parent selection. The metrics chosen by the authors were used as inputs in a fuzzy inference system resulting in a value indicative of the neighboring nodes quality. The obtained results showed that considering the studied scenarios, the OF-FL can improve point-to-point delay, packet loss rate, and network lifetime.

The Context-Aware Objective Function (CAOF) is proposed in [18]. Designed for wireless sensor networks, the CAOF is based on the remaining resources and in the change of the sensor state along the time. The proposed objective function (CAOF) performs a weighted sum of three metrics: node connectivity degree, battery energy level, and node position in the routing tree relative to the parent node. The final goal of the function proposed by this author is to find a delivery probability for each sensor node. The contributions of the above-mentioned studies are considered to propose the Energy Efficient and Path Reliability Aware Objective Function, described in the next section.

IV. Proposed Approach

Based on the current necessity of OFs able to improve the performance of RPL in IoT-based applications, this paper proposes an Energy Efficient and Path Reliability Aware Objective Function (ERAOF). ERAOF is a novel objective function for RPL based on node energy and link quality that aims to optimize the routing process to fulfilling applications that require energy efficiency and data transmission reliability.

As aforementioned, ERAOF is based on two routing metrics: energy consumed (EC) and ETX. Considering EC, ERAOF turns the RPL aware of the network power consumption. Thus, the protocol can choose the path with a low probability of link broken caused by energy exhaustion. Simultaneously, taking into account the ETX, ERAOF enables the RPL to know the quality of link among the network nodes. This feature can decrease the use of connections with less conditions and contribute to an enhanced network performance. With the use of ERAOF, each node computes a value $T(n_i)$, which represents the quality of a node i in terms of its own EC and ETX based in the link for the DIO message sender j as presented in Equation 4.

$$T(n_i) = F_{EC}(n_i) + F_{ETX}(n_i, n_j) \tag{4}$$

Where:

$F_{EC}(n_i)$ is the function that returns the energy consumed by the node i since the beginning of its operation;

$F_{ETX}(n_i, n_j)$ is the function that returns the ETX based on the link between a node i and the DIO message sender j.

Every time that receives a DIO, the node must calculate its $T(n_i)$. After computing it, the node i forwards a DIO to its neighbors with the sum of the calculated value plus $T(n_j)$ (previously received inside of the DIO message). This process allows the nodes to know the quality of its neighbors and, consequently, the quality of the route to the gateway (root) node.

The quality of a route r, in terms of EC and ETX, is defined by $Q(r)$, whose value is given by the sum of the $T(n_i)$ values of the nodes that compose it, according to Equation 5. During the network operation, RPL must select the best route for sending a data message based on the computed $Q(r)$. Thus, considering a set of available paths, the protocol must select the one with the lowest $Q(r)$ value, which represents a route with the best value of the composition of power consumption and ETX.

$$Q(r) = \sum_{i=1}^{j} T(n_i) \qquad i, j, r \in \mathbb{N}^* \tag{5}$$

Next section presents a performance assessment study of the proposed ERAOF in comparison with the most relevant OFs proposals available in the literature.

V. Performance Evaluation and Results Analysis

To evaluate the performance of the proposed OF, the experiments were realized using COOJA [19], an IoT simulation tool available at the Contiki operating system. The proposed ERAOF was evaluated in comparison to other two important objective functions available in the related literature, the OF0 (Objective Function Zero) [13] and the MRHOF (Minimum Rank with Hysteresis Objective Function) [14]. The performance of the three OF was evaluated considering the packet delivery ratio, number of hops, and spent energy for delivered data packet.

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Simulation Time	60 minutes
Initial Energy	20 J
Application	MP2P
Routing	RPL
Mac Protocol	802.15.4
Radio	CC2420
Data message rate	1 msg/min
Numbe of nodes	20, 40, 60
Network deployment	4x5, 5x8, 6x10 grids
Packet length	
Type of packet	Lenght
DIO	16 bytes
DAO	16 bytes
DAO-ACK	4 bytes
DIS	2 bytes
Data Packet	30 bytes

The evaluation study of the proposed OF was performed in three different network sizes. The physical topologies of the scenarios consider 20, 40, and 60 nodes deployed in grid. In the application considered for these networks, all the nodes sent data packets to just one gateway characterizing a multipoint-to-point (MP2P) traffic pattern. The simulations were repeated five times. The results are presented with a confidence interval of 95%. Other simulation parameters are shown in Table I.

Figure 2 exposes the results obtained for the packet delivery rate (PDR) metric. PDR represents the percentage of data packets sent from a sensor node that reaches its destination with success. According to the experiments, the use of ERAOF was able to increase the number of packets delivered when compared to the other approaches, mainly in the network with 60 nodes. Due to the use of the combination of ETX and EC metrics to select the preferred parent, the ERAOF allows the routing protocol to create routes with an efficient energy consumption and high reliability contributing to a reduction of the number of packet loss. Moreover, the proposed ERAOF was able to maintain a high PDR even with the network growing.

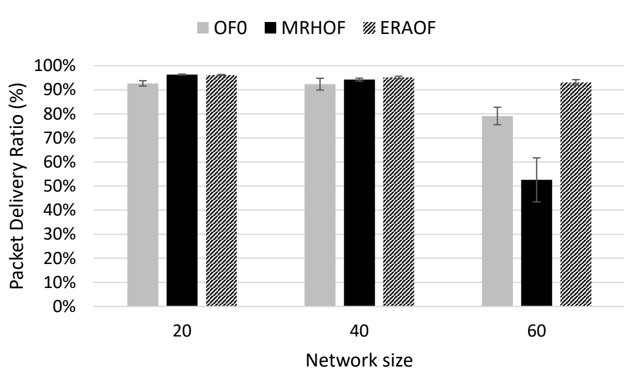

Fig. 2. Packet delivery ratio in function of the network size considering networks with 20, 40, and 60 nodes for OF0, MRHOF, and ERAOF using RPL protocol.

Figure 3 presents the results considering the number of hops. This metric represents the size of the path used by a node to achieve the message destination. Thus, the number of hops shows the number of times that a message is transmitted until reaching its destination. The experiment results reveal that, in small networks (with 20 and 40 nodes), the number of hops used by all the studied approaches is almost equal. However, in the network with the greater size (60 nodes), the MRHOF had a significant increase, in terms of number of hops, exposing its low scalability. On the contrary, ERAOF was able to demonstrate a consistent performance very similar to OF0, which is an OF that seeks the shortest path ever. It is also important to note that routes created with a high number of hops increase the energy consumption due the necessity of more messages forwarding and radio usage.

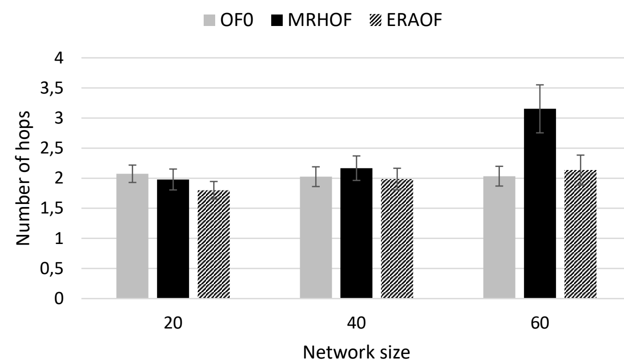

Fig. 3. Number of hops in function of the network size considering networks with 20, 40, and 60 nodes for OF0, MRHOF, and ERAOF using RPL protocol.

Figure 4 shows the results for the spent energy per delivered data packet. This metric reveals the average amount of energy that a node spent for a data message delivery to the gateway (or sink) node. The metric is calculated thought the ratio between the quantity of energy consumed and the number of data packets delivered with success. The obtained results reveal the studied OFs were able to maintain very close results, with the exception of MRHOF OF in the network with 60 nodes. Although ERAOF had obtained better results in the packet delivery ratio when compared to OF0, its performance in this metric was close of OF0. These results show that ERAOF has spent more energy for reaching a high delivery ratio.

VI. CONCLUSION AND FUTURE WORK

This work proposed a new objective function for RPL protocol. The proposal, named ERAOF, aimed to provide energy efficiency and reliable data communication for IoT applications. To reach this main goal, the ERAOF applies the composition of the routing metrics of energy consumed and ETX for select the best path to forward a data message. The performance assessment study shown the proposed OF can increase the packet delivery ratio keeping an effective energy consumption and the use of a low number of hops. Thus, the main contribution of this work is a new objective function for RPL that can offer high packet delivery ratio for IoT

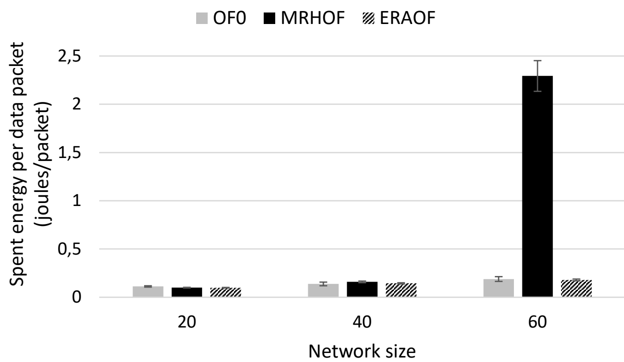

Fig. 4. Spent energy per delivered data packet in function of the network size considering networks with 20, 40, and 60 nodes for OF0, MRHOF, and ERAOF using RPL protocol.

applications with an efficient power consumption of network resources.

For future work, the authors propose a complete performance evaluation study of ERAOF considering different scenarios, metrics, and traffic patterns.

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